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Extensions of least-cost diets through linear programming: three essays

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EXTENSIONS OF LEAST-COST DIETS THROUGH LINEAR PROGRAMMING: THREE ESSAYS

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Extensions of least-cost diets through

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GENERAL INTRODUCTION

Of all the problems that could have been addressed, the problem of nutrition which affects the entire world's masses was addressed. Nutritional problems are of direct concern ranging from the overweight executive in the U.S. to underfed mothers of the third world. Our natural instincts do not necessarily lead us to consume a balanced diet. An understanding of foods and their nutrients is essential for planning nutritionally adequate diets.

This dissertation addresses the problem of designing nutritious diets at minimum cost. Least-cost diets were initially designed by Stigler (1945). Refinements of the model have been undertaken by Smith (1959), Balintfy (1980), Hall (1977), Foytik (1981), and O'Brien-Place and Tomek (1983). In this thesis, models were developed to answer questions not addressed in previous research.

Organization of Thesis

This research is organized as follows. Part One, "Least-Cost American Diets for the 1980s: The Impacts of Improved Information on Nutrition and Health," addresses the effect of increasing the number of nutritional constraints on an optimal diet. The inclusion of "health" constraints, which are recommendations designed to increase longevity and reduce the incidence of certain diseases, is also considered. The coverage of the literature review and the theoretical background is also applicable to the analysis in all three essays.

Part Two presents the second essay, "A Comparison of Type A and Strictly Least-Cost Diets with Plate Waste Considerations and Added Nutrients," which addresses the problem of designing least-cost diets for school children in the National School Lunch Program. Strictly least-cost diets are developed with and without consideration to the childrens' revealed preferences towards foods. Constraints to increase the palatability of the optimal diets are included.

Part Three presents the essay, "Least-Cost Diets in U.S. Famine Assistance to Ethiopia," which addresses the problem of designing least-cost diets for the severely malnourished in Ethiopia as part of a relief effort from the U.S. through the Agency for International Development. A comparison between the FAO's RDAs and the Food and Nutrition Board's RDAs is also analyzed.

Each essay contains its own conclusion. Overall conclusions from the research are briefly summarized following Part Three.

PART ONE. LEAST-COST AMERICAN DIETS FOR THE 1980s: THE IMPACTS OF IMPROVED INFORMATION ON NUTRITION AND HEALTH

Introduction

Global malnutrition is a problem today. Even in the U.S., there are still 29 million people who live below the poverty line, of whom most are not eating properly (Lappe, 1982, p. 101). The Department of Agriculture (1983) recently concluded that the food stamp program has left 91 percent of its recipients nutritionally deprived, partly because of the low level of aid provided, and partly because the food items bought with these stamps were not of the highest nutritional quality. Thus, the food was unable to meet the Recommended Daily Allowances (RDA) of nutrients for proper nutrition and good health, as specified by the Food and Nutrition Board of the National Academy of Sciences (Lappe, 1982, p. 102).

Ironically, the U.S. has a second malnutrition problem, one due to obesity. There is a strong correlation between obesity and the incidence of hypertension, hypercholesterolemia, diabetes, coronary artery heart disease, and cancer (Select Committee on Nutrition and Human Needs, 1979, pp. 1-18).

Many proposals exist that attempt to alleviate both of these malnutrition problems. For example, Frances Lappe in "Diet for a Small Planet," recommends a diet that is primarily meat free because this type of diet is, she claims, the cheapest attainable, while still being nutritionally sound. She also supports the dietary recommendations of the Senate Select Committee, and incorporates these recommendations into specific diets. Yet Lappe's sentiments are not shared by all nutritionists, food producers, or economists.

Nutritionists from both sides of this debate are addressing the United States' two major nutritional problems, low food consumption and obesity, by recommending plausible diets to each group of individuals. However, in most cases the recommendations do not guarantee that all RDA will be met, nor do the recommendations attempt to minimize the cost to the low income groups. Even though the USDA designs "low-cost" food plans for low income families, the poor still spend from one-half to two-thirds of their incomes on these diets (Lappe, 1982, p. 111).

Previous Research

Several attempts to determine nutritionally sound diets at least cost have been made in the past. The first model that determined a least-cost diet was developed by Stigler (1945) using the 1943 RDA. His optimal one year diet for 1939 included 370 lbs. of wheat flour, 57 cans of evaporated milk, 111 lbs. of cabbage, 23 lbs. of spinach, and 285 lbs. of dried navy beans.

One drawback of Stigler's model was that there was no assurance that a person would obtain a nutritionally sound diet on a weekly basis. Although it is not necessary for a person to meet the RDA on a strictly daily basis, it is necessary for the individual to meet these allowances on average over a 5-8 day period (Food and Nutrition Board, 1980, p. 36).

Smith (1959) developed a least-cost diet model with the aid of linear programming. His "midget" model found the least-cost combination of 73 commonly used foods in the Michigan area for a family of three over a four-week period. He used twelve 1953 RDA constraints in the model. (The constraints used in his model are the *'d constraints in Table 1.) Smith's optimal diet for this family included 139 lbs. of whole milk, 4 lbs. of margarine, 6 lbs. of carrots, 83 lbs. of fresh potatoes, 10 lbs. of pork, and 66 lbs. of white flour.

Though Smith reduced the time interval over which the diet would be served, the period of time was still too long to insure proper nutrition on a weekly basis. In addition, Smith's model made no provision for how the food should be divided among the family members. For example, should the woman have consumed the percentage of the diet which corresponded to the (woman's calorie requirement)/(family's calorie requirement)?

Hall (1978) developed a least-cost diet model that incorporated recipes as the activities in the diet, instead of food items. She also included in the cost of the recipe the time and energy costs that went into preparing the recipe. In addition, she included artificial constraints to increase the palatability of the diet. However, the major drawback of her model was that she only included nine nutritional constraints in the model.

Foytick (1981) developed a least-cost diet using updated prices and 12 RDAs. But, again, the model had a limited number of nutritional constraints.

O'Brien-Place and Tomek (1983) developed a least-cost model to measure inflation of food prices during the 1970s. However, one of the drawbacks of their results was that they were unable to obtain feasible solutions with RDAs set at their full level. They had to reduce the RDAs in order to get a feasible solution.

It should be noted that each least-cost diet was not the same. This was due in part to the changing relative prices of the food items, the changing RDA, especially in food energy, and the differing food items incorporated into each model.

There are many nutritional aspects to consider when designing a balanced diet. One of the key aspects of such a diet, which has been largely overlooked, is to achieve adequate levels of the essential amino acids. These essential amino acids include lysine, threonine, methonine and cystine (total sulphur amino acids), tryptophan, valine, isoleucine, phenylalanine and tyrosine (total aromatic amino acids), leucine, and histidine for infants. Because protein sources, especially nonmeat foods, vary in the relative composition of these essential amino acids, it is not sufficient to just meet the minimum protein requirement in aggregate. Nutritionists have demonstrated that the amounts and proportions of protein sources in the diet should be adjusted to satisfy the requirement of each essential amino acid, i.e., there must be amino acid complementarity. The reason that amino acid complementarity is so important is that if any one of the eight essential amino acids is deficient by x percent, then the remaining essential amino acids are in effect reduced to the same level of deficiency because of the unique relationship of combinations that these amino acids have in fulfilling man's protein requirement (Lappe, 1982, pp. 173-174).

Objectives of the Present Study

In this paper we attempt to model a more complete least-cost diet, i.e., to combine the best of all previous research and to add the latest nutritional insights to the least-cost model. The purpose of this paper was to develop least-cost diets and to address the following questions:

1. Would there be a significant difference between Smith's optimal diet and our optimal diet, using Smith's original 12 constraints?

It seemed reasonable to predict that our model would have more variety because we increased the number of constraints from 12 to 56. We also felt that the number of activities would rise because some of the foods in Smith's solution did not contain the trace elements that we included as constraints in our model.

2. Would any of the essential amino acids be binding or limiting?

It has been argued on the one hand that if a diet were completely devoid of meat, then the diet would be deficient in one of the essential amino acids because a least-cost diet would only choose the cheapest protein source, and if that food was a vegetable or grain which was deficient in one or more of the essential amino acids, then the protein requirement would not be met. On the other hand, by including all the vitamin and trace element constraints, the likelihood of binding amino acid constraints was reduced, because one of these additional constraints may have been so binding that it would have forced the model to include an ample supply of amino acids while the model satisfied the trace element requirements.

3. Would any meat items be included in the optimal diet?

The Food and Nutrition Board has suggested that animal products, which are high in good quality protein, need to be consumed because they are important sources of the trace elements, i.e., it would be very unlikely to get the trace elements in a strictly meat free diet (Food and Nutrition Board, 1980, p. 146). Lappe (1982, pp. 89-94) has argued just the opposite. It is her contention that nonmeat items are more cost effective than meats in meeting RDA.

4. Would any of the minerals, vitamins, or trace elements, that had not been included in previous least-cost diet models, including the constraints with upper bounds, be binding?

The trace elements included in this study were: iron, zinc, iodine, copper, manganese, chromium, selenium, and molybdenum. As mentioned, since trace elements could be toxic if overconsumed, it was important to set both upper and lower limits for the consumption of each trace element. Most previous models had only included iron. Thus, our model extended other models by including more trace element constraints.

The minerals included in this study were: calcium, phosphorus, and magnesium. However, it was not sufficient just to meet the minimum RDA for these minerals. The calcium:phosphorus (Ca:P) ratio has been recognized to influence the absorption of calcium and its loss from bone. The available evidence suggested that men and women could tolerate a Ca:P ratio between 2:1 and 1:2 (Food and Nutrition Board, 1980, p. 126).

Therefore, the model included constraints that kept the Ca:P between 1:2 and 2:1. Again, this was a provision not included in previous models.

There were two basic types of vitamins included in the models: water-soluble and fat-soluble vitamins. The water-soluble vitamins included: ascorbic acid (vitamin C), thiamin, riboflavin, niacin, vitamin B6, folacin, vitamin B12, biotin, and pantothenic acid. Deficiency in essential nutrients could lead to diseases such as scurvy as in the case of vitmain C. It was just as important to meet these water-soluble vitamin allowances as it is to meet the protein allowance. Previous least-cost models had tended to overlook the importance of including <u>all</u> of these water-soluble vitamin constraints.

The fat-soluble vitamins included in this study were: Vitamins A, D, E, K. Because of the synthesis of vitamin K by intestinal bacteria in normal individuals, no provision in the model was made to ensure the consumption of it, though the Food and Nutrition Board (1980, p. 50) recommends 70-140 ug. of Vitamin K on a daily basis. An upper constraint on the consumption of vitamin A was also included. Vitamin D could also be toxic, but a specific level of toxicity was not provided by the National Academy of Sciences, and hence, we did not include an upper bound on the consumption of vitamin D.

5. Would any of the dietary recommendations from the Select Committee on Nutrition and Human Needs (1979) be binding?

In general, the recommendations of the Committee on Nutrition included:

- the decreased consumption of fat, including a balancing of the consumption of polyunsaturated, monosaturated and saturated fats in a ratio of 10:10:10;
- the increased consumption of complex carbohydrates;
- the increased consumption of fiber, where fiber was defined as the sum of the indigestible carbohydrate and carbohydrate-like components of food, including cellulose, lignin, hemicelluloses, pentosans, gums, and pectins (Food and Nutrition Board, 1980, p. 32);
- the decreased consumption of sodium; and
- the decreased consumption of cholesterol.

There has been and there still is some controversy concerning these constraints. For example, the Salt Institute stated that for over fifty years salt had been the principal source of iodine, a necessary nutrient important in the prevention of goiter. In order to obtain the RDA of iodine from iodized salt, they claimed that three grams of table salt had to be consumed per day. In addition, salt added to prepared foods was not iodized. Therefore, if total salt intake (including salt in foods and table use) was restricted to three grams per day, as the committee recommended, then they concluded that the incidence of endemic goiter could be expected to increase (Dietary Goals for the United States, 1979, p. 684). We did not include these health constraints because we necessarily endorsed them, but to see how they would affect the cost of our least-cost diet and the corresponding activity levels.

6. Would there be any difference in the activities and binding constraints between a model designed for females and a model designed for males?

Men and women have differing nutritional needs. The National Academy of Sciences had also stated that there were limitations to the approach of planning one diet by summing up the RDA of each member of a particular nutritional target group. Specifically, for individuals whose energy needs are relatively low, such as women and the elderly, it was especially critical to insure that foods of high nutrient density are selected to provide an adequate supply of all nutrients, whereas for those with high energy needs, e.g., adolescent males, foods of lower nutrient concentration were adequate (Food and Nutrition Board, 1980, p. 13).

7. Would multiple vitamin pills be cost effective supplements in a least-cost diet?

Many nutritionists have argued that using vitamin supplements are not necessary if an individual was eating a balanced diet from a variety of foods. We agree with this point. However, we were interested to see whether or not multiple vitamin pills could significantly reduce the cost of a least-cost diet.

Model and Methods

In order to solve the problem of finding the least expensive diet that satisfies all RDAs, a linear programming model was built and an IBM MPSX/360 Computer Routine was used. Linear programming is a mathematical procedure for determining the optimal combination of activities subject to one or more constraints. In this case, we were interested in the optimal mix of foods that satisfied nutrient and health criteria at least cost.

Linear programming applies directly only to situations in which the effects of different activities in which we can engage are linear. The linearity requirement in our model consisted of three general facets:

a. The effects of a single variable or activity by itself were proportional; e.g., doubling the amount of milk consumed would double the cost of drinking milk for the individual; e.g., there were no discounts given for bulk buying,

b. The interactions among variables had to be additive, e.g., the dollar cost of the diet was the sum of the dollar cost of all individual food items that were to be consumed,

c. The variables had to be continuous; i.e., fractional values for the activities were allowed; e.g. a person could have eaten 33.666 g of bananas (Schrage, 1984, p. 3).

We feel that these three simplications of linearity are consistent with the least-cost diet problem for single individuals.

The general model we used can be expressed in the following manner:

(1) minimize $C = \Sigma p_j \cdot f_j$

(2) subject to $\Sigma a_{ij} \cdot f_j <=> R_i$ $(j = 1, 2, \ldots, n)$ and $(i = 1, 2, \ldots, m)$,

(3) $f_j \geq 0$, $p_j \geq 0$, $\sim a_{ij} \geq 0$ for $(j = 1, 2, \ldots, n)$ and $(i = 1, 2, \ldots, m)$

where C was the minimand, or in this case the total cost of the diet for the one week period;

p_js were the prices of the edible 100 gram portions of the jth food item;

f_js were the levels of the jth food item, i.e., the activity or the actual amount of food that was to be consumed;

R_is were the nutritional constraints, i.e., they were the RDA that had to be met in order to assure proper nutrition; and

a_{ij}s were the nutritional units of the ith RDA supplied per 100 grams of the jth food item.

The linear programming models that we developed minimized the cost of a diet (the objective function) given the nutritional composition of a group of foods (the a_{ij} matrix) subject to the fulfillment of all the RDA for a healthy, moderately active male or female between the ages of 23-50. The prices used in the model came from a sample of 4 grocery stores in Ames, Iowa. No one store carried all food items in the model. The prices used in this model were averages of the prices at the stores where that food item was available. It should also be noted that some prices were seasonal, as the price information was gathered in early November of 1984. This was important, as small price changes in some food items would have affected the final composition of the least-cost diet. (This will be illustrated later in the article under range analysis.) However, this sensitivity does not constitute a methodological drawback, since a least-cost diet could have been developed for each season or month of the year.

It should also be noted that the opportunity costs in terms of time for preparation, cleanup, energy, shopping, etc., were not included, as Hall (1977, pp. 35-38) included in her least-cost model. We felt that the consumer could weigh the marginal costs of such variable activities against the marginal benefits from those same activities in maximizing his or her utility from eating, and disutility from preparation.

We obtained the information for the a_{ij} matrix, i.e., the compositional data of the food items, from the HVH-CWRI Nutrient Base (Food and Nutrition Encyclopedia, pp. 802-989). The primary reason that our model had only 129 food items was that the compositional data for both the essential amino acids and the fatty acids in food items were limited, and the two lists did not contain compositional data on the same foods. (If it was found that amino acid constraints were not binding, then future models would only have a protein constraint, and this would consequently allow for the inclusion of more food items to be analyzed.)

There were two assumptions underlying the a_{ij} matrix: all the items were to be consumed by the individuals in the quantitites indicated, and the data used in the computations were both relevant and reliable. It should also be noted that the compositional data reported was the mean value of the jth nutrient found in any ith food. The values were supposed to represent typical year-round, countrywide values. Therefore, the aij matrix should be generally applicable (Eckstein, 1983, p. 257).

We obtained the nutritional restrictions for the model from the ninth edition of Recommended Dietary Allowances (1980). The majority of the RDA constraints in the model were set up with lower limits. This was done because most, but not all, nutrients were tolerated well in amounts that exceeded the allowances by as much as two to three times, and a substantial proportion of the population commonly consumed an excess over the RDA for several nutrients without evidence of adverse effects (Food and Nutrition Board, 1980, p. 30). But there were exceptions to this rule. We included upper limits on the following nutrients which had been proven to have toxic effects: vitamin A, molybdenum, selenium, copper, manganese, and chromium. In addition we included an upper limit of ten percent of dietary energy that could be in the form of polyunsaturated fatty acids to reflect the possible hazards of high intakes of polyunsaturated oils (Food and Nutrition Board, 1980, p. 36). In certain cases, a range of intake was given instead of an absolute minimum level. We used the lower number in the interval as the lower limit.

In order to answer the seven questions raised, we ran four major models in a total of ten runs. First, we ran a model using Smith's original 12 constraints, while monitoring the dietary levels of the other constraints in our expanded model. Since relative prices had changed since 1955, and since the RDA for these 12 constraints had also changed, it was reasonable to predict that the activities in our least-cost diet would differ from the activities in Smith's solution. We also addressed the differences between a male and female solution by running individual models for both. Since Smith's model did not contain vitamin supplements as a potential activity, we ran both of these submodels with multiple vitamins included and with multiple vitamins excluded from the list of food items. Therefore, we ran four versions of this model: a female model which included vitamin supplements, a male model which included vitamin supplements, a female model without vitamin supplements, and a male model without vitamin supplements. Table 1 lists the daily nutritional requirements used in the four model formulations. The *'s show Smith's 12 original constraints.

Table 1. Constraint levels used in the four least cost diet model formulations

Nutritional constraint[a]	Nutritional allowance/day: Female - 55 kg.	Male - 70 kg.
1. Water	variable	variable
*2. Calories (kcal) =	2000	2700
*3. Protein (g) L	44	56
4. Cystine (mg) L	275	350
5. Histidine (mg) L	220	280
6. Isoleucine (mg) L	660	840
7. Leucine (mg) L	880	1120
8. Lysine (mg) L	660	840
9. Methionine (mg) L	275	350
10. Phenylalanine (mg) L	440	560
11. Threonine (mg) L	440	560
12. Tryptophan (mg) L	165	210
13. Tyrosine (mg) L	440	560
14. Valine (mg) L	770	980
*15. Total fat (g) U	∞/77.77	∞/105
16. Saturated fat (g) U	∞/22.22	∞/30
17. Saturated fat (g) L	11.11	15
18. Polyunsaturated fat (g) U	22.22	30
19. Polyunsaturated fat (g) L	17.78	24
20. Oleic acid (mono) (g) L/=	0/22.22	0/30
21. Linoleic acid (g) L	6.7	9
22. Cholesterol (mg) U	∞/300	∞/300
*23. Carbohydrates (g) L	75/1925	75/2599
24. Fiber (g) L	∞/15	∞/15
25. Calcium (mg) U	1600	1600
*26. Calcium (mg) L	800	800
27. Phosphorus (mg) U	1600	1600
*28. Phosphorus (mg) L	800	800
29. Sodium (mg) U	∞/3300	∞/3300
30. Sodium (mg) L	1100	1100
31. Magnesium (mg) L	300	350
32. Potassium (mg) L	1875	1875
*33. Iron (mg) L	18	10
34. Zinc (mg) L	15	15
35. Copper (mg) U	3	3
36. Copper (mg) L	2	2
*37. Vitamin A (mcg RE) L	800	1000
38. Vitamin A (mcg RE) U	25000	25000

[a] L = constraint with a lower limit; U = constraint with an upper limit; * = Smith's 12 original constraints, ∞ = no upper bound.

Table 1. Continued

Nutritional constraint[a]	Nutritional allowance/day	
	Female - 55 kg.	Male - 70 kg.
39. Vitamin D (IU) L	200	200
40. Vitamin E (IU) L	15	15
*41. Vitamin C (mg) L	75	60
*42. Thiamin (mg) L	1	1.4
*43. Riboflavin (mg) L	1.2	1.6
*44. Niacin (mg NE) L	13	18
45. Pantothenic acid (mg) L	5.5	5.5
46. Vitamin B6 (mg) L	14	15.4
47. Folacin (ug) L	400	400
48. Biotin (ug) L	100	100
49. Molybdenum (mg) U	0.5	0.5
50. Molybdenum (mg) L	0.15	0.15
51. Selenium (mg) U	0.2	0.2
52. Selenium (mg) L	0.05	0.05
53. Chromium (mg) U	0.2	0.2
54. Chromium (mg) L	0.05	0.05
55. Manganese (mg) U	5	5
56. Manganese (mg) L	2.5	2.5
57. Iodine (ug) L	150	150
58. Vitamin B12 (ug) L	3	3

Results and Discussion

Smith's formulations (Models 1a and 1b)

The optimal diet for each sex under Smith's original formulation plus vitamin pills (Smith VP) is shown in Table 2, columns 1 and 2. The cost of this diet for a week was \$3.03 for the female and \$3.48 for the male. In this model, both the male and the female ate the same food items, but the female consumed more dry milk and vitamin supplements, while the male consumed more white four.

Table 3, column 1, shows that the binding nutritional constraints were the same for both males and females, as were the shadow prices for each constraint. (The shadow prices or dual price, is the dollar amount by which the cost of the diet will increase if one of the RDA is increased by one unit.) For example, if the calcium allowance had been increased by 1 mg in the female model, then the cost of the diet would have risen .0003 cents. The shadow prices were constant over certain intervals of intake, given by the range analysis. To illustrate, again with the case of calcium, the range analysis showed that the shadow price was constant over the interval 773 mg/day to 3097.7 mg/day. If, ceteris paribus, the calcium requirement were increased to 3097 mg/day, then the cost of the diet would have increased by .689 cents/day or 4.82 cents/week.

In the two versions of the Smith model without vitamin supplements (Smith B), Table 2, columns 3 and 4, the optimal diet had more variety. But, the cost of the diets rose from \$3.03 to \$3.95 for the female and from \$3.48 to \$3.92 for the male. Interestingly, in the model with

Table 2. Optimal diets for a one-week period[a]

	Smith VP[b]		Smith B[b]		Basic		Health		Pooled	
	F	M	F	M	F	M	F	M	Basic	"Health"
Cost ($)	3.03	3.48	3.95	3.92	7.70	7.34	8.23	8.05	14.98	16.22
Food item (g):										
White bread					1791	2352	1959	2889	3913	4167
Wheat germ					196	254	254	204	510	509
Flour white	3083	4462	4077	4372		1326	472	773	2059	1855
Cooked eggs					1021	369	306	338	1027	718
Apple					330	388	425	373	706	770
Green grapes					236	450	513	272	843	949
Butter						13		52		9
Skim milk							809	421		1951
Evapor. milk					642	646	554	598	1285	1070
Peanut butter					790	592	506	647	1380	1205
Cabbage cooked							524	227		66
Carrots cooked				14			1334	785		1391
Potatoes baked					800			676		
One-a-day vit.	7.9	6.2			5.3	6.2	5.0	4.8	14.0	11.6
Jelly grape					7	5	6	6	11	10
Salt			203		1124	759	20	6	23	35
Corn oil						80	39	76		
Dry whole milk	794	536	498	520						
Grapefruit			1268	985						
Raw peaches										604
Red beets, can									265	

[a]All activities are rounded to the nearest gram, except for the multivitamin pill which is expressed in the number of pills to the nearest tenth. F = female and M = male.

[b]Smith VP: with vitamin supplements.
Smith B: without vitamin supplements.

Table 3. Shadow prices of limiting constraints in models

Constraint (cents)	Smith w/ vitamins	Smith w/o vitamins		Basic		Health		Pooled	
	F & M	F	M	F	M	F	M	Basic	"Health"
Calories	.00009		.00009	.00005	.00009	.00037	.00002	.00007	.00002
Total fat		.00017							
Polyunsat. fat					.00090	.00747	.00137	.00119	.00319
Oleic acid						.00081	.00143		.00176
Carbohydrates						.00146			
Cholesterol							.00006		.00008
Fiber						.01444	.01366		
Calcium	.00030	.00033	.00028	.00023	.00025	.00021	.00037	.00037	.00026
Phosphorous				.00019	.00025		.00020	.00020	.00027
Sodium					.00000		.00000		.00000
Iron		.01158							
Zinc				.00030	.00027	.00033	.00032	.00028	.00035
Copper				.18714	.18678	.17983	.18692	.18713	.18655
Vitamin A U						.00000			
Vitamin D		.00005	.00009						
Vitamin C	.00007	.00119	.00122	.00007	.00007				
Vitamin B6						.00355	.00205		
Folacin				.00104	.00086	.00087	.00020	.00104	.00036
Biotin				.00148	.00148	.00143	.00146	.00147	.00152
Molybdenum				.43365	.24820	1.1573	1.4033	.42852	1.2807
Selenium				.00020	.00171		.00192	.00063	.00251
Chromium						.00009			
Manganese			.00619	.00580	.00822	.02762	.01772	.00460	.03588
Vitamin B12				.02673	.02721	.02869	.01861	.02815	.02269

vitamin pills the female diet was 13 percent cheaper than the male diet. Without vitamin pills, however, the female diet had become .8 percent more expensive than the male diet. One possible explanation is that vitamin pills are high-nutrient activities, and the penalty for excluding vitamins from the female diet was greater than the penalty for excluding vitamins from the male diet, because females have fewer calories to use to meet all of their nutritional allowances.

The basic formulation (model 2)

The second major model run was the least-cost diet with updated RDA and dietary constraints, but with no provisions as yet for the health considerations recommended in the Dietary Guidelines. We labeled this model the "basic" model. Table 1 shows the 58 constraints used in both the "basic" model and the "health" model. Where an R_i varied between the two models, the first entry in each column was the value used in the "basic" model, and the second entry was the value used in the "health" model. For example, constraint 22, cholesterol, had no upper limit in the "basic" model (* = infinity), but there was a limit of 300 mg in the "health" model.

The optimal diets for each sex are shown in Table 2, columns 5 and 6. The cost of the "basic" female diet was $7.70 and the cost of the "basic" male diet was $7.34.

The binding constraints for these diets are shown in Table 3, columns 4 and 5. We immediately noted that five of the six trace elements added to the model, manganese, seleuium, molybdenum, copper, and zinc, were binding constraints. Vitamin B12, a vitamin which vegetarians should conscientiously consume because of its relatively low supply in nonmeat items, was also binding. Polyunsaturated fat was also limiting in this model even though we placed no upper bound on fat consumption.

The health formulation (Model 3)

The third model was modified by including health constraints recommended in the Dietary Guidelines, and/or by the Food and Nutrition Board (1980), to reduce the incidence of those diseases which may be caused by the overconsumption of certain foods. The specific recommendations included in this study were:

1. reduce cholesterol consumption to 300 mg. per day,

2. reduce salt consumption to 3300 mg. per day,

3. increase fiber consumption to 15 grams per day,

4. increase carbohydrate consumption to account for 55 percent of caloric intake, and

5. reduce saturated fat consumption to 10% of total energy intake, and balance saturated with polyunsaturated and monosaturated fats, so that each accounts for approximately 10% of energy intake (Select Committee on Nutrition and Human Needs, 1979, p. 6).

The optimal diets are shown in Table 2, columns 7 and 8. The cost of the female "health" diet was $8.23 and the cost of the male health diet was $8.05. The addition of the health constraints had made the female diet more expensive than the male diet. Despite the addition of six constraints, the number of food items increased by only three (skim milk, cabbage, and carrots) over the "basic" model. The main difference between the basic and health formulation lay rather, in the relative consumption among the selected food items.

The inclusion of the health constraints also added four nutrients to the binding constraints in the model: fiber, cholesterol (male), carbohydrates (female), and monosaturated fat. In other words, in some cases meeting one health requirement simultaneously satified another.

The pooled formulation (Model 4)

We also ran a model that targeted the nutritional requirements of the female and male as one consuming unit. We labeled this model the "pooled" model. We did this to see how the activities of the model would differ from the separate male and female diets and to reflect family purchasing and cooking patterns. We ran the model once with the basic constraints and once with the health constraints. The optimal diets are shown in Table 2, columns 7 and 8.

The cost of the "basic pooled" diet was $14.98. The cost of the "pooled" diet with the health constraints was $16.22.

Apart from the flour, the female "health", male "health", and pooled "health" models were felt to be quasi-palatable. The inclusion of the health constraints caused the program to choose more foods. Ironically, the inclusion of the health constraints led to an increase in the consumption of white bread. This was contrary to the current recommendations of nutritionists who advocate whole grain breads to meet the fiber requirement and may be explained by the vitamin enrichment of white bread by many producers. The "pooled" results showed that the cost of each "pooled" diet was less than the combined cost of the two individual diets, \$14.98 vs. \$15.04 for the "basic" diet, and \$16.22 vs. \$16.28 for the health diet. In addition, the activity levels in the "pooled" models were not the same as the algebraic sum of the levels in the individual models. These two points led us to conclude that adding the RDA of different individuals was not a linear combination, and hence solutions obtained with a "pooling" of requirements would give an incorrect solution.

Conclusions

One general aspect of the results should be viewed with caution: the shadow prices. When determining the most binding constraint in a diet model, one should not just look for the highest shadow price in Table 3. In determining the most cost restrictive constraint in the diet, it was misleading to look at just the shadow prices of the nutrients because even if the nutrients were measured in the same units, the actual number of mg or ug required for each nutrient was not the same. For example, a male, who was eating the "health" diet, needed 700 ug of biotin per week and 21 ug of vitamin B12 per week. Though the shadow price of vitamin B12 was greater than the shadow price of biotin, vitamin B12 was not actually the more cost restrictive constraint. A more relevant measure is to look at the effect of increasing or decreasing a particular nutrient allowance by one percent, i.e., a proportional change in the nutritional requirement, as opposed to just a one unit change. A one percent change in biotin represents 7 ug, while it only represents 0.21 ug of vitamin B12. Multiplying each one percent change by the respective shadow price, we came up with the cost flexibility of each nutrient. For example, we found that a one percent increase in the biotin requirement raised the cost of the diet by .01022 cents, while a one percent increase in the vitamin B12 requirement, only raised the cost of the diet by .00391 cents. Hence, there was a 2.6 times greater cost to increasing the biotin requirement than raising the vitamin B12 requirement by one percent, even though the shadow price of vitamin B12 was over 12 times greater than the shadow price of biotin.

As to the overall objectives of the study, we found the following results:

1. There was a significant difference between our solutions and Smith's solution. Using just Smith's original 12 constraints, our model had fewer activities (four in each case), and only one food item in common, white flour. When we expanded to the "basic" model, our solution had four of Smith's six optimal foods, and twice as much variety. The diets would have had even more variety, if it were not for the inclusion of the multiple vitamin pills. Finally, the cost of the least-cost diets for the female rose from $3.03 in the Smith model with vitamin supplements to $8.23 in the "health" model, and similarly from $3.48 to $8.05 for the male. Most of the increase was due to the additional nutritional constraints, not the "health" constraints.

2. The amino acid constraints were not binding. Each amino acid was in slack by 300 percent to 700 percnet. This corresponded with the

fact that the slack activity in the overall protein row ranged from 80 percent to 100 percent, corresponding to current levels of protein consumption in the U.S. today (USDA, 1983, p. 1). The implication of this finding is that it is not necessary to include individual amino acid constraints for U.S. diet models given our current levels of nutritional knowledge and food availability.

3. No meat items came into any of the optimal solutions. Interestingly, the increase in the cost of the diet to include 100 grams of meat was greater than the actual cost of the meat. For example, the cost to include 100 grams of hamburger in the female "health" diet was 36 cents, which was greater than the price of the meat, 28 cents.

4. Some of the additional nutritional constraints added to Smith's model were binding. Of the 28 added mineral, vitamin, and trace element constraints, 16 of the constraints were binding in at least in one model, and ten were binding in each of the "health" diets. This was important because we felt this was what contributed to the increased variety of our diets. Also, the upper limit on phosphorous consumption was binding. This suggested that people may be consuming too much phosphorus relative to calcium.

5. Of the five health recommendations included in the model, three were binding in the female model, fiber. fat, and carbohydrates, and four were binding in the male model, fat, cholesterol, fiber, and sodium. The fiber and fat constraints were common constraints for both models. As mentioned, the cost penalty for these constraints was greater for the female diet than it was for the male diet.

6. There was a difference between the optimal foods for females and for males in the first three models. In addition, the "pooled" diets did not have the same activities as did the corresponding divided model. Except for the first two versions of the first model, the binding constraints also differed.

7. Vitamins were found to be cost effective as supplements, as illustrated by the three models that included vitamin supplements as a food item. Also, the plotted demand curve for multiple vitamin pills was very inelastic. Specifically, if the price of the vitamins were to increase 434 percent for a female who was consuming the "health" diet, her consumption of vitamins for that one week would decrease by only two percent (.1 of a pill), i.e., the demand for vitamin supplements was very inelastic.

The sensitivity analysis of the model showed that all of the optimal activities, except vitamin pills, were fairly sensitive to changes in the prices of the food items. For example, suppose the price of a one pound loaf of bread rose by just one cent (three percent), then a woman consuming the "health" diet, would reduce her consumption of bread from 1981 grams to 1805 grams (nine percent). Hence, changes in the diet due to individual tastes and preferences, which could have been included in the model with artificial constraints, would have not significantly raised the cost of the diet, but would have instead changed the activity levels in the optimal diet.

Future Research Directions

This research leads us to suggest four possible directions for further nutritional research:

1. Nutritionists and food scientists should concentrate on analytical techniques that more accurately measure the composition of food items which contain those RDA constraints which were both significantly binding in our model and which consumption studies show to be typically lacking in U.S. diets.

2. Nutritionists should engage in research that more accurately defines the RDA for those constraints which were binding in our model. Increases or decreases in the current RDA levels would thus increase or decrease the cost of the least-cost diet and affect optimal diet composition. In a similar vein, research into the RDA of trace elements which were not included in our model is also warranted. It would allow for a more complete model, which we think would add variety and palatability.

3. Researchers should define upper levels on amino acid consumption and/or set ratios for the consumption of the amino acids. Unless new evidence comes to light, least-cost diets will be complete if they do not make specific provisions for the essential amino acid requirements, as the other RDA insure that they will be met, as is evidenced by our results.

4. Pharmaceutical companies should conduct research that would lead to the development of low cost vitamin and mineral supplements for those vitamins and minerals that were binding in our model and that are

presently being under-consumed here in the U.S. and throughout the world.

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PART TWO. A COMPARISON OF TYPE A AND STRICTLY LEAST-COST DIETS WITH PLATE WASTE CONSIDERATIONS AND ADDED NUTRIENTS

Introduction

In 1978, school food service was the second largest away-from-home food market, having a value of $7-8 billion, with the federal share being 30 percent (LaChance, 1978, p. 73). Virtually all of school food service is provided by the National School Lunch Program (NSLP). This program, begun in 1947, was authorized by Congress to safeguard the health of the nation's children and to encourage the domestic consumption of nutritious agricultural commodities (Radzikowski and Gale, 1984, p. 454).

The mission of the NSLP is to provide school children with nutritious and appealing lunches. Food waste is doubtlessly inevitable in any institutional food system. However, when an excessive amount of food served to children is not consumed, the mission of the school lunch program is not being fully achieved in two important regards:

1. such plate waste could be an important indication that unappealing food is being served, and

2. food when discarded has no nutritional value for children, causing a decrease in the effectiveness of the NSLP (Jansen and Harper, 1978, p. 395).

A recent review of attitudes and food habits discussed the various classes of food-related attitudes important to menu plannners and concluded that these attitudes should be explicitly assessed in order to avoid planning menus with unknown or generally unacceptable foods. For example, children do not generally like vegetables, except for corn and potatoes; therefore, school lunch menus should avoid serving too many vegetables (Eckstein, 1983, p. 15).

Effective school food service requires the amalgamation of a well-managed food delivery system, an effective nutrient delivery system, and a systematic food, nutrition, and health education system (LaChance, 1978, p. 73). This paper focuses on the improvement of the nutrient delivery system.

The nutrient delivery system is dependent upon food quality, menu planning, food merchandising, preference assessment, and food acceptance. This paper emphasizes preference assessment, i.e., measurement of individuals' attitudes towards food items, and food acceptance, i.e., percent consumption of a food item (Eckstein, 1983). Food acceptance implicitly takes into account food quality because of the positive relationship between the two. For example, the fresher the food, the more likely it will be consumed. Hence, a model which takes into account the preference assessments and food acceptance of children is more likely to design a menu children will eat.

Certain aspects of the nutrient delivery system, e.g., menu planning and food merchandising, are best handled by each school district. According to Balintfy and Nebel, computerized menu planning probably will always be a joint person-computer decision making activity because there are a number of aspects of the menu planning process that may never be sufficiently defined to allow incorporation into the model (Eckstein, 1983, p. 236). For example, variation in preparation method often reflects work load rather than consumer considerations (Eckstein, 1983, p. 30).

Currently, there are two main types of menus schools serve to children, the "nutrient-based" and the "Type A pattern" menus. The nutrient-based diet explicitly meets the Recommended Daily Allowances (RDA) set by the U.S. Department of Agriculture (USDA) for the NSLP. By contrast, the Type A menu plan consists of:

1. one serving of meat or meat alternate, where a serving is: 2 oz. of lean meat, poultry, or fish, or 2 oz. of cheese, or one large egg, or 1/2 cup of cooked dry beans or peas, or a combination of any of the above;

2. two or more servings of vegetable or fruit or both to total 3/4 cup;

3. one serving of bread or a bread alternate, where a serving is: one slice of whole-grain or enriched bread, or a whole-grain or enriched biscuit, roll, muffin, etc., or 1/2 cup of cooked whole-grain or enriched rice, macaroni, noodles, whole-grain or enriched pasta products, or other cereal grains such as bulgar or corn grits, or a combination of any of the above; and

4. a serving (8 fl. oz.) of milk (Radzikowski and Gale, 1984, p. 458).

The pattern was designed as a <u>guide</u> for providing approximately one-third of the RDA for calories and ten nutrients (protein, fat, iron, calcium, phosphorus, vitamin C, vitmain A, riboflavin, thiamin, and niacin) for boys and girls ten to 12 years old (Lilly et al., 1980, p. 7).

Separate studies have demonstrated that the Type A pattern does not provide the nutrient delivery advantages of a nutrient-defined menu-planning approach. Type A menus have failed to meet 1/3 of the RDAs for many nutrients. Studies on the adequacy of these diets have shown iron, thiamin, and calories were the nutrients most often below the standard. These deficiencies were just for lunches as served (LaChance, 1978, p. 75).

For lunches actually consumed, studies have shown vitamin A, phosphorus, calcium, and protein were additionally underconsumed. The reason for the additional deficiencies was that the prepared food was either not selected or it was discarded (Lilly et al., 1980, p. 8). Another study confirms that school lunches as actually consumed do not provide 1/3 of the RDAs for magnesium, vitamin A, vitamin B6, calcium, and iron (Radzikowski and Gale, 1984, p. 455).

Additionally, neither the Type A menu nor the nutrient based menu explicitly provides for the RDAs of certain vitamins, trace elements and minerals, such as vitamin E, copper, zinc, molybdenum and phosphorus. Failure to include all current RDAs in a least-cost nutrient based model will lead to a solution which underestimates the least-cost of a well balanced diet and which may provide for a different set of foods to be consumed (Faiferlick et al., 1985).

The Type A pattern also fails to consider the changing food preferences of children. The extent of food waste varies by food item. For example, milk has had the highest acceptability and consumption rate of any food category (LaChance, 1978, p. 75). Consumption data have also indicated raw and cooked vegetables were the least accepted and least consumed foods. For other food categories (fruits and juices, desserts, bread, and starches) percentage consumption varied greatly (Lilly et al., 1980, p. 8).

The final criticism of the NSLP concerns commodity donations from the USDA. USDA donated foods are a source of inefficiency in the NSLP for the following reasons:

1. Due to the high cost of transporting, storing, handling, and processing donated commodities into usable products, the cost of donated foods is actually higher than the cost of locally acquired products.

2. Some donated foods are difficult to use in preparing meals and increase the cost of operating a food service program.

3. Uncertainty of delivery dates and the bunching of deliveries at the end of the school year overload local storage capacity, increase costs, and make menu planning difficult.

4. Donated foods are often packaged in unusable forms for use by schools, including items children simply do not like and which often arrive in a damaged state.

5. Serving donated commodities lowers student participation and increases waste in the school lunch program.

6. Current regulations impose an excessive burden on school districts (Puma and St. Pierre, 1983, p. 80).

Thus, the USDA could assist school districts better by subsidizing hot lunch programs with cash or commodity-specific chits.

Models have been built to design palatable least-cost diets for school aged children. Balintfy has developed a menu planning model based on preference attitudes. His research indicated that whole milk should be a frequent menu item, but, that it would be wiser to serve it slightly less often than at present, i.e., not every day (Balintfy et al., 1980, pp. 54-62).

However, Balintfy's study used a quadratic model based on preference surveys. The main criticism of preference surveys is that foods rated higher than other foods are not necessarily preferred more often than foods with a lower preference rating. Recent studies (Eckstein, 1983, pp. 21-22) have revealed that some foods:

1. were liked and would be selected frequently, e.g. milk, orange juice, toast, eggs, apples, and bacon; preference was critical and not subject to monotony, i.e., normal goods with little or no diminishing marginal utility,

2. were liked very well but would be selected less frequently, e.g., steak, fried chicken, corn on the cob, French fries; these foods were subject to monotony which overrides preference, i.e., luxury goods with diminishing marginal utility,

3. were not liked as well but would be selected frequently, e.g., bread, margarine, potatoes; these foods are not subject to monotony and preference is less critical, i.e., necessity goods with little or no diminishing marginal utility.

Thus, a high measured preference towards a particular food does not necessarily mean children would be satisfied with frequent consumption of it. Nor does a high preference result in less plate waste, if that food item is subject to monotony.

Finally, although Balintfy's model maximized utility by maximizing ordinal rankings, the single most important predictor of participation in the NSLP has been shown to be price (Mauer, 1984, p. 425). Furthermore, a diet resulting from a model which reduces the cost of a school lunch, while still excluding unpopular foods, is more likely to be consumed than a diet that only attempts to maximize utility. Hence, a model that maximizes utility does not necessarily minimize plate waste if foods that are subject to diminishing marginal utility must be served frequently in the diet.

One way to measure the actual preferences of children in the NSLP is through the use of surveys to measure plate waste. Plate waste measures both reveal the preferences of children towards certain foods and provide an explicit percentage of consumption for a food item. They are good predictors of overall consumption (Eckstein, 1983, pp. 260-269). Most important, simple methods exist for school food service directors to measure plate waste (LaChance, 1978, p. 76).

Objectives of the Study

In this paper, models were designed to address the following questions:

1. Is there any significant difference betweeen diets designed for girls and for boys in the same age group?

Previous research has shown least-cost diets are not the same for men and women (Faiferlick et al., 1985). Boys and girls in each age category have different RDAs and energy requirements, i.e., girls require food with a higher nutrient density than boys. Hence, there should be a difference in the two diets.

2. Is there any significant difference in diets designed for each age group?

Nutritional requirements also vary among children according to age because of differences in their physiological states. For example, high school girls have the same or greater need than junior high school girls for all nutrients except calories. Thus, high school girls may need to consume foods of higher nutrient density than junior high school girls.

3. Is there a difference between an optimal diet with plate waste constraints and one without these constraints?

Children have low preferences towards vegetables. Since vegetables are a cheaper source of many nutrients than meats, nuts, etc., (Faiferlick et al., 1985) then using plate waste measures to make vegetables relatively more expensive than other foods should raise the cost of the optimal diet and may exclude most vegetables.

4. Is there a significant difference between the composition of a least-cost nutrient base diet and a least-cost Type A NSLP diet?

By adding constraints to make a least-cost diet more palatable, the cost of the optimal diet will either remain the same or increase because the set of available foods that can be choosen has been reduced. Thus, if a least-cost nutrient based diet consists of only three or four foods, then a Type A least-cost diet will be more expensive because previously excluded foods will be substituted for the cheaper foods.

5. Does the complexity of the diet increase when the number of nutritional constraints is increased?

The use of dietary complexity as a measure for nutrient intake is gaining status in nutrition literature. Schorr et al. (1972) found a positive relationship between dietary complexity and nutritional quality of diets of teenagers. Sanjur and Scoma (1971) found a similar relationship for preschool children. The relationship implies a complex and varied diet increases the likelihood foods containing essential nutrients will be consumed (Yperman and Vermeersch, 1979, pp. 72-73). Currently, there are only 11 RDA stipulations for the NSLP. This contention was tested by expanding the number of RDAs to 32 by including all the known RDAs for the remaining vitamins, minerals, and trace elements. Thus, an increase in RDAs from 11 to 32 should increase the number of foods in the optimal diet. However, the increase in nutritional constraints should also raise the cost of the optimal diet.

Model and Methods

A linear programming model was built to solve the problem of determining least-cost diets for school children, given their nutritional requirements and revealed preferences towards foods. Linear programming can determine the optimal combination of activities subject to one or more constraints. In this case, the model found the optimal mix of foods that satisfied nutrient constraints given the food consumption habits of school children at least cost.

The general model can be expressed in the following manner:

(1) minimize $C = \Sigma p_j \cdot f_j$ over a two-week period (ten lunches),

(2) subject to $\Sigma a_{ij} \cdot f_j <=> R_i$ $(j = 1, 2, \ldots, n)$ and $(i = 1, 2, \ldots, m)$

(3) $f_j \geq 0$, $p_j \geq 0$, $a_{ij} \geq 0$ for $(j = 1, 2, \ldots, n)$ and $(i = 1, 2, \ldots, m)$, and

(4) yi $\geq$ or $<$ a constant for $(i = 1, 2, \ldots, n)$

where C was the minimand or, in this case, the total cost of the diet for the two-week period.

pjs were the prices of the edible 100 gram portions of the jth food item.

fjs were the levels of the jth food item, i.e., the activity or the actual amount of food to be consumed; USDA donated products were excluded as possible activities in the optimal diets because of the high final cost and unappealing nature of the foods. Instead, only commercially available foods were used in the model.

Ris were the nutritional constraints, i.e., 1/3 of the RDAs to be met in order to assure proper nutrition.

aijs were the nutritional units of the ith RDA supplied per 100 grams of the jth food item.

yis were variety constraints which required that a certain kind of food be consumed at a minimum, a maximum, or a fixed level over the two-week period. Kind is defined as a food group set upon the basis of a common characteristic, e.g., asparagus is a kind of vegetable and lime is a kind of fruit.

Studies have shown that children and young people have more pronounced likes and dislikes than do more mature adults. For this reason, children will accept more repetition of those menu items they like (Eckstein, 1983, p. 22). Hence, a two-week cycle would not be an objectionable cycle over which to plan a menu.

The prices used in the model came from a sample of four grocery stores in Ames, Iowa. No one store carried all food items in the model. The prices used in this model were averages of the prices at the stores where the food item was available. In addition, some prices were seasonal, as the price information was gathered in early November of 1984. This was important, as small price changes in some food items would have effected the final composition of the least-cost diet. However, this sensitivity does not constitute a methodological drawback, since a least-cost diet could have been developed for each season or month of the year.

Next, these prices were retail prices, not the wholesale prices charged to a school lunch program. However, this consideration did not effect the food mix of optimal diets if one assumes the wholesale prices charged to schools were a constant percentage of the retail price. Only the cost of the least-cost diet was overestimated.

Finally, the production costs in terms of time for preparation, cleanup, energy, purchasing, etc., were not included. As noted earlier, this consideration was a work load factor which is best handled by the school district. In addition, it was assumed these production costs were fixed regardless of the type of food served. Hence, it was assumed the marginal production cost for adopting a least-cost diet was zero, hence, production considerations had no effect on the optimal solutions.

The plate waste measures (Jansen and Harper, 1978, pp. 397-398) were incorporated into the model by raising the price of each food item to represent the amount of food that would have to be purchased in order for children to actually consume 100 grams of it. For example, ten percent of all milk served in the NSLP is discarded. If one assumes on average that all children discard ten percent of the milk served to them over the two week period, then to ensure these children receive, on average, the nutrient content of 100 grams of milk on a daily basis, 111 grams of milk should be served every day.[1]

The compositional data of the food items, i.e., the aij matrix, was obtained from the Highland View Hospital-Case Western Reserve University Nutrient Data Base. There were two assumptions underlying the aij matrix:

1. all the items were to be consumed by each student in the quantities indicated, and

2. the data used in the computations were both relevant and reliable (Eckstein, 1983, p. 257).

It should also be noted that the compositional data reported was the mean value of the jth nutrient found in any ith food. The values were

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[1]The cost per 100 grams consumed was calculated by dividing 100 grams by (1 - the percentage of plate waste). In this case, 100/(1 - 10%) = 111.11. This "plate waste index" was then multiplied by the market price of 100 grams the food item. As the percentage of plate waste increased, so did the effective price of the food item.

supposed to represent typical year-round, nationwide values. Therefore, the a_{ij} matrix should be generally applicable.

The nutritional restrictions for the model were obtained from the ninth edition of Recommended Dietary Allowances, (Food and Nutrition Board (FNB), 1980). The majority of the RDAs constraints in the model were set with lower limits. This was done because most, but not all, nutrients were tolerated well in amounts that exceeded the allowances by as much as two to three times, and a substantial proportion of the population commonly consumed an excess over the RDAs for several nutrients without evidence of adverse effects (Food and Nutrition Board, 1980, p. 10). But there were exceptions to this rule. The model included upper limits on the following nutrients which had been proven to have toxic effects: vitamin A, molybdenum, selenium, copper, manganese, and chromium (FNB, 1980).

Finally, the essential amino acid constraints were excluded from the model for two reasons:

1. amino acid composition of all the activities did not exist; and

2. previous research has shown the inclusion of the other RDAs included in this model insures a surplus of the essential amino acids (Faiferlick et al., 1985).

Results

To answer the five questions raised, five models were run a total of 22 times.

Gender differences

The first model addressed the question of whether or not there was any difference in diets separately designed for boys and girls. This question was tested two ways. First, optimal diets using the full set of nutritional constraints were designed for a grade school boy and girl, both of whom had identical nutritional requirements, for a junior high school boy and girl, and for a high school boy and girl, all without consideration to plate waste measures. (The nutritional constraints are in Table 1.) The optimal diets for the boys are in columns 1, 2, and 3 of Table 2 and the optimal diets for the girls are in columns 1, 2, and 3 of Table 3. The foods in the diets were almost identical except that boys consumed peanut butter and girls did not. The main difference between each girl's and boy's diet was the relative consumption of each food. Intuition suggests that since girls consume fewer calories than boys, then girls should also consume a smaller amount of each food item. But this was not the case. Girls tended to consume more of the food items with a lower fat content, e.g., skim milk, baked potatoes, and appples, while boys tended to consume more of the foods with a higher fat content, e.g., whole milk and eggs. Finally, in both cases, the cost of the girls' diets were cheaper than the boys' diets. This result reversed the findings of previous research which showed least-cost diets for female adults were more expensive than least-cost diets for male adults (Faiferlick et al., 1985). The primary reason for this reversal is that adult women require foods that have higher nutrient densities than adolescent girls.

Table 1. RDAs for the ten-day-lunch cycle over a two-week period[a]

	Boys/girls	Boys		Girls	
Age group:	7-10	11-14	15-18	11-14	15-18
Constraint:					
Calories, kcal (E) *	8000	9000	9333	7333	7000
Protein, g (G) *	113	150	187	153	153
Calcium, mg (L) *	2667	4000	4000	4000	4000
Phosphorus, mg (L) *	2667	4000	4000	4000	4000
Sodium, mg (L)	2000	3000	3000	3000	3000
Magnesium, mg (L)	833	1167	1333	1000	1000
Potassium, mg (L)	3333	5083	5083	5083	5083
Iron, mg (L) *	33	60	60	60	60
Zinc, mg (L)	33	50	50	50	50
Copper, mg (U)	8.3	10	10	10	10
Copper, mg (L)	6.7	6.7	6.7	6.7	6.7
Vitamin A, IU (L) *	2333	3333	3333	2667	2667
Vitamin D, IU (L) *	1333	1333	1333	1333	1333
Vitamin E, mg (L)	23	27	33	27	27
Vitamin C, mg (L) *	150	167	167	200	200
Thiamin, mg (L) *	4	5	5	4	4
Riboflavin, mg (L) *	5	5	6	4	4
Niacin, mg (L) *	53	60	60	50	47
Pant, Acid, mg (L)	13	13	13	13	13
Vitamin B-6, mg (L)	5	6	7	6	7
Folacin, ug (L)	1000	1333	1333	1333	1333
Biotin, ug (L)	400	333	333	333	333
Molybdenum, mg (U)	1	1.7	1.7	1.7	1.7
Molybdenum, mg (L)	0.33	0.5	0.5	0.5	0.5
Selenium, mg (U)	667	667	667	667	667
Selenium, mg (L)	166	166	166	166	166
Chromium, mg (U)	667	667	667	667	667
Chromium, mg (L)	166	166	166	166	166
Manganese, mg (U)	10	17	17	17	17
Manganese, mg (L)	7	8	8	8	8
Iodine, ug (L)	400	500	500	500	500
Vitamin B12, ug (L)	10	10	10	10	10

[a]U = upper limit, L = lower limit, E = equals, and * = RDA used in the 11 RDA model.

Table 2. Boys' optimal diets for ten-day-lunch cycle

	w/o plate waste index			w/ plate waste index		
Age group:	7-10 (boys/girls)	11-14	15-18	7-10 (boys/girls)	11-14	15-18
Cost ($)	4.00	4.29	4.39	5.08	5.52	5.35
Food item (g):						
White bread	42	754	806	-	1113	680
Wheat germ	-	11	-	145	116	45
Eggs	1281	1187	1109	38	326	896
Margarine	61	30	216	351	163	226
Apple	169	106	293	240	219	271
Banana	-	263	207	4	205	45
Butter	-	-	15	-	-	-
Cheese, Amer.	-	3	-	-	-	-
Whole milk	1835	666	545	3210	2892	2261
Skim milk	-	1278	1486	-	-	-
Peanut butter	488	494	89	133	-	-
Baked potatoes	1114	567	1887	2047	1779	2627
Grape jelly	-	4	4	-	4	3

Table 3. Girls' optimal diets

	w/o plate waste index			w/ plate waste index		
Age group:	7-10 (boys/girls)	11-14	15-18	7-10 (boys/girls)	11-14	15-18
Cost ($)	4.00	4.03	4.11	5.08	5.21	5.09
Food item (g):						
White bread	42	751	721	-	764	535
Wheat germ	-	30	30	145	34	56
Eggs	1281	1021	1019	38	990	917
Margarine	61	25	-	351	-	-
Apple	169	334	321	240	308	334
Banana	-	32	274	4	41	-
Cheese, Amer.	-	3	4	-	4	-
Whole milk	1835	462	457	3210	1121	372
Skim milk	-	1667	1675	-	1041	1873
Peanut butter	488	-	-	133	-	-
Baked potatoes	1114	2217	1887	2047	2197	2777
Grape jelly	-	4	4	-	4	3
Black pepper	-	-	10	-	-	4

Secondly, the model was modified to incorporate plate waste measures. This was done by changing the prices of the foods to reflect the amount of food that had to be served in order to ensure consumption of 100 grams. The optimal diets for the boys are in columns 4, 5, and 6 in Table 2, and the optimal diets for the girls are in columns 4, 5, and 6 of Table 3. As in the first version of the model, there was no significant difference in the diets, except that boys consumed peanut butter and whole milk, whereas girls consumed more baked potatoes, no peanut butter, and partially substituted skim milk for whole milk.

Age differences

The second question addressed whether or not there was any difference among optimal diets according to age. The results were obtained by reconsidering the results in Tables 2 and 3. The general results were the same in all three age categories, i.e., there were only minor differences between the food items and consumption levels of junior high school boys and girls and high school boys and girls. However, there was a more significant difference between the optimal diets of grade school students, and the junior high and high school students. There was a difference in both the foods which made up the diets and the relative consumption of the foods common to the optimal diets. This difference was more significant for girls than boys.

Plate waste considerations

The third question, whether or not including a provision for plate waste measurements would alter the foods of an optimal diet, was also addressed with the results in Tables 1 and 2. As expected, the plate waste measures did increase the cost of the diet for each sex and age group. Even though there was only a small change in the food items consumed in each diet, there was a change in the relative consumption of the foods between the two diets. Milk and potato consumption increased significantly for boys and girls consumed more skim milk when plate waste measures were included.

Type-A diets

The fourth question dealt with the difference between a least-cost diet and a Type A least-cost diet for high school boys and girls. (A Type A least-cost diet is a diet that meets the variety stipulations of a Type A diet at least cost. The prices used in both models reflected plate waste considerations.) Three versions of the model were run. The optimal diets for the first version of the Type A diet which just met the specifications as outlined on pages 2-3, are in columns 1 and 4 of Table 4 for a high school boy and girl respectively. Foods in the optimal diets and their relative consumption were very similar, except the boys consumed larger amounts of margarine, and popcorn. The girls also substituted 938 grams of skim milk for the 2270 grams of whole milk the boy consumed.

The second version required four (2 oz.) servings of meat over the ten lunch period. In addition, to avoid monotony, the consumption of baked potatoes was limited to one serving every other day or 500 grams over the menu cycle. These two artificial constraints caused the two diets to be even more similar than in the first version (columns 2 and 5 of Table 4). The entire meat requirement was met for both the boy and girl by consuming 250 grams of Braunschweiger. The only differences were the boy ate more margarine and grape jelly than the girl.

A third version of the high school model required that the meat requirement be met by four different types of meats (columns 3 and 6 of Table 4). The four meat items included in the optimal diet were Braunschweiger, ground lamb, flank steak, and roast beef. This constraint made the boy's and girl's diets even more similar. The only difference this time was that the boy should consume more margarine. This reflected his greater need for calories. In fact, the difference in the cost of the two diets, \$7.55 - \$7.18 = \$0.37 is roughly equivalent to the difference in the value of margarine consumed, {(422 - 88) grams x \$0.12/gram} = \$0.40.

Expanded RDA set

The final question asked whether or not decreasing the number of nutritional constraints would alter the optimal diets. The optimal diets for the 32-constraint case have already been shown in Tables 2, 3, and 4. To determine optimal diets with only the current 11 constraints used by the NSLP, we developed four more optimal diets (Table 5). The model was run for a grade school boy and a high school boy with and without plate waste considerations. Clearly our expanded model with 32 nutritional

Table 4. Optimal Type A diets for ten-day-lunch cycle[a]

	Boys			Girls		
Age:	15-18	w/ VAR 15-18	w/ MV 15-18	15-18	w/ VAR 15-18	w/ MV 15-18
Cost ($)	5.89	6.62	7.55	5.60	6.24	7.18
Food item (g):						
White bread	250	250	250	250	250	250
Wheat germ	189	168	218	255	168	219
Eggs	302	123	110	301	123	110
Margarine	156	351	422	-	9	88
Tuna	114	133	152	115	133	151
Apple	239	89	186	256	85	185
Banana	-	613	731	-	602	725
Grapefruit	-	500	286	-	515	293
Flank steak	-	-	60	-	-	60
Roast	-	-	60	-	-	60
Lamb	-	-	63	-	-	63
Braunschweiger	-	250	62	-	250	62
Van. ice cream	388	22	334	351	66	383
Whole milk	2270	2270	2270	1332	2270	2270
Skim milk	-	-	-	938	-	-
Peanut butter	-	249	-	-	256	-
Popcorn	289	-	23	-	-	12
Bkd. potatoes	2720	500	500	2728	500	500
Grape jelly	-	18	-	-	-	-
Salt	-	-	-	-	4	-
Black pepper	-	18	24	-	17	54

[a]VAR = variety constraints included in the model and MV = meat variety constraints included in the model.

Table 5. Optimal diets for boys/11 RDA casefor ten-day-lunch cycle

	w/o plate waste		w/ plate waste	
Age:	7-10	15-18	7-10	15-18
Cost ($)	2.21	2.91	2.62	3.43
Food item (g):				
White bread	1007	2160	1036	2039
Margarine	26	-	270	-
Grapefruit	-	350	75	-
Van. ice cream	1253	1471	1233	1377
Skim milk	-	95	-	279
Baked potato	716	125	576	782

constraints caused each respective diet to be more diverse. For example, the grade school boy consumed three more foods in Table 1 than in Table 5.

Table 6 shows the shadow prices of the binding nutritional constraints from the optimal diets determined for the grade school and high school boys using 32 RDAs (columns 1-4) and using 11 RDAs (columns 5-8). Except for Vitamin C, the RDA's that are binding in the 11 RDA case were also binding in the 32 RDA case. There were from three to eight more binding constraints in the 32 RDA case, depending on which diet was considered.

Conclusions

1. School lunch programs do not necessarily have to offer different foods to boys and girls to ensure adequate nutritional intake for each. However, either the portions served should not be the same or toppings and sauces should be provided so that boys can meet their higher calorie requirements.

2. Plate waste constraints have a minor impact on least-cost diets. The plate waste measures in least-cost diets affect the quantities to be provided rather than the foods to be included in the optimal diet. The most important point was that the cost of the optimal diets rose approximately 26 percent with plate waste considerations, suggesting that current waste in the NSLP is of at least that magnitude.

3. School lunch districts that prepare meals at one site should not serve grade school students the same meals as junior high school and high

Table 6. Shadow prices/boys ($) ($10^{-5}$)

	32 RDA case				11 RDA case			
	w/o plate waste index		w/ plate waste index		w/o plate waste index		w/ plate waste index	
Age group:	7-10	15-18	7-10	15-18	7-10	15-18	7-10	15-18
Constraint:								
Calories	15	15	17	16	15	12	16	12
Calcium	-	17	-	8	28	31	28	34
Copper	841	3560	9878	4921	-	-	-	-
Magnesium	-	2	-	-	-	-	-	-
Iron	-	344	86	1186	421	543	1110	1152
Zinc	-	20	-	38	-	-	-	-
Vit. D	81	28	81	64	-	-	-	-
Vit. C	-	-	-	-	110	113	159	131
Thiamin	2114	-	-	-	-	-	-	-
Vit. B6	5603	9524	11190	13953	-	-	-	-
Folacin	-	-	41	-	-	-	-	-
Biotin	151	151	211	214	-	-	-	-
Selenium	96	182	78	130	-	-	-	-
Vit. B12	-	227	-	-	-	-	-	-

school students. Because grade school students have different nutritional requirements and preferences towards foods, a conscious effort should be made to distinguish the diets in order to increase consumption and to meet the nutrtitional requirements of both groups.

4. Variety constraints increased the cost of the optimal diets by more than 40 percent. Additional variety and/or health constraints would also increase the cost of an optimal diet.

5. An increase in the number of nutritional constraints increased the number of foods in the optimal diets. Thus, eating a variety of foods is, as nutritionists argue, the best way to ensure consumption of all necessary nutrients.

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PART THREE. LEAST-COST DIETS IN U.S. FAMINE ASSISTANCE TO ETHIOPIA

As late as 1974, the World Food Council resolved that all governments should strive to ensure that by 1984 "no child, woman or man goes to bed hungry and that no human being's physical or mental potential is stunted by malnutrition." Yet, starvation remains in the world spotlight because approximately 9 million people in Africa face a serious nutritional threat, and death is already occurring in some regions, e.g., Ethiopia (Council on World Hunger, Development, and Trade Information, 1984, p. 1).

The U.S. is committed through Public Law 480 (PL 480) to reducing malnutrition caused by famine. Under Title II of the program, the Agency for International Development (AID) and the U.S. Department of Agriculture donate agricultural commodities "to meet famine or other urgent or extraordinary relief requirements" (Knutsen et al., 1983, p. 149). Commodities are made available to friendly governments by the Commodity Credit Corporation (CCC) through voluntary relief agencies such as CARE. AID is responsible for the overall supervision of program operations, including assuring effective use of the commodities in the recipient country.

While, PL 480 has delivered almost 660 billion pounds of food worth $34 billion over its 14 year existence (AID, 1984, p. 1), steps to improve famine assistance are always warranted. One approach to increasing the impact of a limited amount of aid is to minimize the cost of providing nutritious diets to famine victims. Least-cost diets for developing countries have been designed by Florencio and Smith (1970, pp. 207-230) for Columbia. They concluded that least-cost diets could deliver more economical nutrition for a target group. Their least-cost diets often had as much variety as the current diets of the poor in the world; thus, the lack of palability, a common criticism of American least-cost diet models, was not a critical drawback. In fact, in the less developed countries restricted menus are satisfactory as most consumers seek primarily to satisfy their physiological needs (Eckstein, 1983, p. 14). Florencio and Smith (1970, p. 229) concluded that the desire for variety may be largely a goal of the affluent -- a legitimate goal, but hardly one to be sought at the expense of an adequate intake of the major nutrients.

Researchers have also used linear programming to design high protein mixes such as the Blended Food Product-Formula No. 2, Corn-Soy-Milk (CSM). CSM is a blended food supplement consisting of heat processed corn meal, toasted soy flour, nonfat dry milk, and a premix of minerals and vitamins. The distribution of CSM by AID has brought generally favorable response and good acceptance (Cavins et al., 1972, p. 46).

Objectives of the Study

In this paper, we use linear programming to determine least-cost diets for the severely malnourished of Ethiopia and to address the following questions:

1. What are the optimal diets for each target group in Ethiopia? Will there be any significant difference in the composition among the optimal diets?

There are two reasons for designing least-cost diets for Ethiopia:

a. to minimize the cost of short run famine assistance for AID. Because AID funds are limited ($1 billion for food aid in 1983), then minimizing the cost of providing optimal diets to famine victims will allow AID to provide more assistance in Ethiopia and worldwide;

b. to ensure that famine relief provided to the Ethiopians will be nutritionally beneficial. Because of the dire nutritional status of many people, it is important that they receive all the nutrients necessary to improve and maintain their health, all the more so because a contributing cause of malnutrition is that people often consume the wrong combination of foods (Finot, 1974, p. 125).

The FAO (1974, pp. 66-68) has established recommended intakes for certain target groups: infants, children, adolescent males, adolescent females, pregnant women, lactating women, adult males, and adult females. Specific RDA's are not established for people 51 years old and older.

Nutritional needs vary according to age and gender. For individuals whose energy needs are relatively low, such as the 51+ age group, it is especially critical that foods of high nutrient density be selected to provide an adequate supply of all nutrients, whereas for those with high energy needs, e.g., adolescent males, foods of lower nutrient concentration are adequate (FNB, 1980, p. 13).

Development literature also supports the contention that diets will vary according to age and sex. Berg (1981 pp. 27-28) states that efforts to attack the problem of malnutrition must address the needs of people of all ages and both sexes, as opposed to the tendency of nutrition assistance programs to focus almost exclusively on the needs of children and pregnant and lactating women. Otherwise, common family decisions to share food aid will circumvent the intended goals of a famine assistance program.

2. Will an optimal diet using FAO's RDAs differ from one using RDAs established by the Food and Nutrition Board (FNB)? What effect will the inclusion of amino acid constraints have on the optimal diets? What will be the most constraining nutrients in the diet?

Thirty-three RDAs have been established in the U.S. for calories, protein, essential amino acids, minerals, and vitamins. However, the FAO has established RDAs for only 18 nutrients. Of these 18 RDAs, the FAO's RDAs were in most cases less than the FNB's RDAs, yet both organizations claimed that their recommendations were at a level which ensured the nutritional well being of "nearly all" healthy people. The FAO concluded that new nutritional knowledge may allow some of the RDAs to be fixed more precisely, but they felt that major changes would be unlikely (FAO, 1974, p. 66). Previous research has shown that as the number of nutritional constraints increase, so does the complexity of the diet (Sanjur et al.). Indeed, nutritionists in the U.S.A. recommend diverse diets so that nutrients which do not have specific RDAs can be met.

Essential amino acid constraints are used in the model instead of the protein efficiency ratio (PER), used by the FAO. The PER is one of the least satisfactory procedures for assaying protein quality because it fails to consider possible linear protein complementation (Pellet and Pellet, 1983, p. 415).

Essential amino acid constraints are also included in our model because only 23 foods (Table 1) are currently being provided to Ethiopia by AID. As the number of food items decreases, the probability that an essential amino acid could be binding or limiting increases. Of the essential amino acids, only four are likely to be limiting: lysine, threonine, tryptophan, and total sulfur amino acids (SAA). Of these four amino acids, methionine (total SAA) and lysine are by far the most frequent limiting amino acids (Pellet and Pellet, 1983, p. 418). However, previous research has also shown that essential amino acid constraints have been nonbinding in least-cost diets which had to simultaneously meet all of the known FNB's RDAs (Faiferlick et al., 1985).

3. Can AID foods be used in place of vitamin supplements in the early treatment of protein-energy malnutrition (PEM)?[1]

The first step in famine assistance is the treatment of the severely malnourished. Mortality rates for this group have been high. The high risk for severe malnutrition stems mainly from three factors:

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[1]There are three forms of clinical protein-energy malnutrition: 1) marasmus, 2) marasmic kwashiorkor, and 3) kwashiorkor (World Health Organization (WHO)), 1981, p. 7.

Table 1. The cost ($/metric ton) for AID to purchase foods for Ethiopia (May 1985)[a]

Food item	Price	Food item	Price
Wheat	158	Beans	475
Vegetable oil	672	Soy flour	380
Butter	110	Soy-fortified (SF) bulgur	230
Cheese	110	Wheat flour	228
SF flour	302	Bulgur (par-boiled wheat)	220
Wheat-soy blend	326	Corn	145
Cornmeal	204	SF cornmeal	225
Sorghum	132	SF sorghum Grits	214
SF rolled oats	361	Instant CSM (ICSM)	297
Corn-soy-milk (CSM)	311	Corn-soy blend (CSB)	391
Rice	310	Peas	315
Lentils	585		

[a]Transportation costs are $130/ton U.S. flag or $80/ton foreign flag. Distribution costs are $100/ton.

• malnutrition induces metabolic alterations that effect the mechanisms of absorption and utilization,

• malnutrition interferes with cellular immunity, and this results in increased susceptibility to infection; and

• malnutrition induces derangements of the fluid and electrolyte control mechanisms and results in dehydration and excessive electrolyte losses.

The WHO (1981, pp. 7-45) has established a rehabilitative nutrition program for the severely malnourished. Since the child with PEM nearly always suffers from diarrhea and vomiting, one of the most dangerous complications of PEM, dehydration, will result. After dehydration has been eliminated, infections commonly associated with severe PEM must be treated. It is recommended that children of all ages be given antibiotic therapy, in order to increase the effectiveness of the subsequent feeding program.

The aim of feeding during the first week is to provide the child with <u>some</u> energy and protein without provoking vomiting and/or diarrhea. The strength and volume of the feeds are gradually increased and the frequency of feeding decreased over the next few days. The next step in correcting PEM is, as rapidly as possible, to eliminate the weight deficit that always occurs in severe PEM. Though the formation of new tissue requires protein, large quantities of protein are not required. It is the energy intake that chiefly determines the rate of "catch-up" growth. Thus, a "high-energy formula" is needed.

During the treatment of PEM, there are other nutrient deficencies that must be addressed. Most children with severe PEM suffer in deficencies from potassium, iron, folic acid, and vitamin A. In addition, most of these children are likely to be deficient in other vitamins, e.g., B complex, C, and D. Throughout the rehabilitation period, these deficiencies are best supplied by multivitamin preparations (WHO, 1981, p. 17).

Although much research and activity have been devoted to the management of PEM, wide divergences of opinions and practices prevail (Ifekwunigwe, 1981, p. 389). Suskind (1981, pp. 403-410), who has recommended a milk-based formula for the treatment of PEM, has also established supplementary RDAs that should be provided in the form of vitamin supplements. But, nutritionists suggest that RDAs should be met by the consumption of a variety of food items, whenever possible.[1]

4. What is the difference between the cost of an optimal diet for a lactating mother and a mother who is not breast feeding? Is the difference greater than the cost of feeding an infant directly?

Production theory would suggest that if humans are like other mammals in the sense that they are ineffficent in converting feed protein into protein for human conumption (Pellet and Pellet, 1983, p. 413), then the cost to feed a mother an optimal diet so that she can lactate should

[1]Because a complete set of rehabilitative RDAs has not been established, and there is disagreement concerning the RDAs that have been established and the length of treatment for those suffering from PEM, a dynamic programming model could not be used to determine the optimal diets over the course of rehabilitation.

be greater than the cost to feed the mother and child separate optimal diets.

Yet Pellett and Pellett (1983, p. 412) recommend that infants should be breast fed, primarily to reduce the potential of child infection due to poor quality water. They further argue that infantile malnutrition may be caused less by food and nutrient deficiency and more by many interrelated socioeconomic and hygenic factors. However, prepared infant formulas correctly used are both nutritionally sound and economically affordable (Pellet and Pellet, 1983, p. 411).

5. What effect do transportation charges have on least-cost diets? Does sending the food via foreign flag as oppossed to domestic flag affect the optimal diets?

The cost to ship food by foreign flag is $80/ton and the cost by U.S. flag is $130/ton (Alo, 1985). Obviously, it would be cheaper to send the food by foreign flag. But will the optimal diet sent be the same? Because the transportation cost per ton of food is constant, and the prices of the foods are different, then adding or subtracting a fixed cost to each food will represent a different percentage change in the price of each food. Hence, the relative price ratios of the commodities will change, and if the optimal diet is sensitive to price changes, then the optimal diet may change.

Model Formulation

We developed a linear programming model to determine least-cost diets for the severely malnourished in Ethiopia.

The objective function was to minimize the cost to AID[1] of providing famine assistance in the form of optimal diets to the severely malnourished, subject to the nutritional requirements of each population subgroup.

In general, the model is:

minimize $\Sigma C_j X_j$ = cost of famine assistance for AID

subject to

$$a_{11}X_1 + a_{12}X_2 + \ldots + a_{1n}X_n <=> R_1$$

$$\cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdots \quad \cdot \quad \cdot \quad \cdot \quad \cdot$$

$$\cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdots \quad \cdot \quad \cdot \quad \cdot \quad \cdot$$

$$\cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdots \quad \cdot \quad \cdot \quad \cdot \quad \cdot$$

$$a_{m1}X_1 + a_{m2}X_2 + \ldots + a_{mn}X_n <=> R_m$$

$$X_j \geq 0 \ , \ a_{ij} \geq 0$$

where C_j = the cost of the jth food item plus the transportation cost to Ethiopia plus the distribution cost of the food within Ethiopia.[2]

In 1985, only 23 food items were available to be shipped to Ethiopia because other commodities did not meet the following criteria (Omololu, 1983, p. 481):

- long shelf-life.

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[1]AID is the decision maker in this model, not the United States.

[2]The cost data for the food items were obtained on request from AID and the CCC. The CCC stated that storage waste for stored foods amounts only to .09 percent, which was less than current commercial waste rate. Therefore, an inclusion for foregone opportunity costs to the CCC was not included as the cost was relatively small.

- easy transportation and packaging - this is why most of the foods are in the forms of powders, flours, or grits.
- versatility - the foods must be in a form that can be used in many ways to conform to local eating habits. Fluids and thin porridges are acceptable all over the world as foods for infants and children. Also, breads and pastes are often consumed.
- easy preparation.

a_{ij} = the amount of nutrient i in the jth food; the compositional data for the AID foods came from two sources: the CRC.

R_i = the Recommended Daily Allowance of the ith nutrient; the RDAs used in the designing the optimal diets for each target group were FAO standards. (The FNB RDAs were used in testing the difference between the two sets of RDAs.)

Results and Discussion

In order to answer the five question raised five models were run a total of 50 times.

Target group differences

The first question raised, addressed the nature of and possible differences among optimal diets for each target group in Ethiopia. The optimal diets are described in Table 2. All target population groups consumed wheat-soy blend (WSB) and butter in varying amounts. WSB was consumed by teenagers and nonpregnant adults because it was the cheapest source of Vitamin C.

Table 2. Optimal daily diets for all target groups

Age group:	Infants	1-3	4-6	7-9	10-12 Boys	10-12 Girls	13-15 Boys	13-15 Girls
Cost ($/day))	0.156	0.162	0.200	0.208	0.248	0.223	0.277	0.241
Food item (g)::								
ICSM	185	-	-	-	-	-	-	-
WSB	16	201	202	50	50	50	75	75
Butter	68	91	113	64	67	67	94	81
Cheese	64	-	35	118	154	129	146	128
Sorghum	-	-	50	304	373	330	382	313
SFCM	-	-	-	-	-	-	7	8

Age group:	16-19 boys	16-19 girls	Adult male	Adult female	Preg.	Lact.	51+[a] male	51+[a] female
Cost ($/day)	0.292	0.224	0.303	0.256	0.318	0.333	0.394	0.384
Food item (g):								
ICSM	-	-	-	-	-	-	140	160
WSB	75	75	75	75	252	252	10	43
Butter	96	77	96	4	93	103	39	-
Cheese	156	118	195	282	38	73	371	180
Sorghum	413	282	24	-	-	-	-	-
SFCM	7	8	-	-	-	-	1	-
Wheat	-	-	272	116	110	116	-	-
SF bulgur	-	-	78	132	140	132	96	-
Lentils	-	-	-	-	-	-	-	886

[a]Diets for 51+ age group were determined with U.S. RDAs, not FAO RDAs.

For children ages 7 through 19, sorghum was the major diet constituent. Adult males and 4-6 year olds also consumed a small portion of sorghum. In addition, children 4-19 consumed cheese.

Wheat and SF bulgur were consumed only by adults. The fact that wheat and sorghum make up a major part of the optimal diets is interesting because wheat and sorghum are common staples eaten in Africa (Pellet and Pellet, 1983, p. 415).

Infants and the 51+ age group were the only groups to consume ICSM.[1] The result that ICSM was the major component of the infant diet was fortunate as infants should consume mostly liquid foods (Pellet and Pellet 1983, pp. 412-413). In addition, the 51+ age group consumed wheat flour.

The FAO did not provide RDAs for the 51+ age group. Thus, optimal diets for the 51+ age group were determined by using U.S. RDAs. However, caution should be used in comparing the diets of the 51+ age group with the rest of the target groups because, as noted below, U.S. RDAs significantly increased the cost of the optimal diets and it also altered the composition of the optimal diets.

RDA differences

The second question addressed whether or not differences between RDAs established by the FAO and FNB would effect optimal diets. The question was tested by substituting the FNB's RDAs into the model. Diets

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[1] We assumed that if water quality was poor that it could be boiled.

were determined for seven target groups (Table 3). The inclusion of the FNB's RDAs resulted in a higher cost for all optimal diets.

There was also some change in the composition of the optimal diets. Sorghum dropped out of the optimal diets for children and was replaced with ICSM, wheat and SF bulgur. Wheat consumption increased significantly for adults, while cheese was no longer consumed and butter consumption fell. In addition, adults began to consume ICSM. Adult and lactating women also consumed more wheat flour.

Another difference in the two sets of RDAs is that the FAO has not established RDAs for the essential amino acids. Instead, the FAO recommends that the protein requirement should be met by protein sources of the same quality as egg or milk protein. Protein-efficienty ratio (PER) are used to relate low quality protein to the egg/milk protein standard. But, to add the PER of different food sources fails to take into account the possibility of essential amino acid complementation. Thus, the FNB's RDAs of the essential amino acids were used.

However, the essential amino acid constraints were not binding. Optimal diets were exactly the same as those in Table 2. The fact that the FNB's RDAs for essential amino acids were used was not a drawback, if one assumed that the FNB's RDAs for essential amino acids were as proportionately great as the other 18 FNB RDAs were to the corresponding FAO RDAs. Consequently, this re-inforces the finding that essential amino acids were nonbinding constraints in least-cost diets.

Table 3. Optimal daily diets using FNB RDAs in place of FAO RDAs

Age Group	7-9	Adult male	Adult female	Lact.	Infant	13-15 male	16-19 female
Cost ($)	0.342	0.428	0.419	0.487	0.180	0.404	0.414
Food item (g):							
Wheat	316	479	533	481	67	515	476
SF bulgur	118	189	117	178	32	119	120
ICSM	144	121	75	100	179	127	127
WSB	58	75	75	150	23	75	75
Butter	40	14	-	12	-	-	19
Cheese	96	-	-	-	82	-	-
Wheat flour	-	-	138	137	-	60	99

The essential amino acid constraints were also added to the model that incorporated the FNB's RDAs. Again, there was no effect on the optimal diets. The optimal diets were the same as those in Table 3.

The binding constraints of the optimal diets from Table 2 are shown in Table 4. All constraints were set with lower bounds. Instead of reporting the shadow prices, which represent the cost or savings from increasing or decreasing a nutritional requirement by one unit, cost flexibility[1] measures were used. Cost flexibility measures the cost or savings from increasing or decreasing the nutritional requirement by one percent.

The calorie constraint was not only limiting in all diets, it was also the most costly constraint except for infants and 1-3 year olds.

Niacin was both the second most frequently occurring and the second most costly constraint[2]. It was binding in diets from the 4-6 year old group through adults.

Another frequently binding and costly constraint was riboflavin. It was binding in all of the same diets as niacin, except in the case of lactating women and adult women. Vitamin D was binding in childrens' diets up to the age of 12 years and in pregnant and lactating women.

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[1]Cost flexibility is the cost to increase or decrease a constraint by one percent. It is found by multiplying the shadow price of the constraints by one percent of the total RDA level.

[2]Cost flexibility rankings were determined by determining the mean value in the diets which it was binding.

Table 4. Cost flexibility of the binding constraints of the optimal diets in Table 2 ($) ($10^{-4}$)

Age group:	Infants	1-3	4-6	7-9	10-12 male	10-12 female	13-15 male	13-15 female
Constraint:								
Calories	1.64	6.80	9.15	11.0	13.3	11.8	14.5	12.5
Iron	0.22	-	-	-	-	-	-	-
Copper	3.27	-	-	-	-	-	-	-
Vitamin D	10.8	9.60	3.20	0.80	0.80	0.80	-	-
Vitamin C	-	-	-	-	-	-	1.11	1.11
Riboflavin	-	-	3.51	4.15	5.11	4.47	5.41	4.77
Folacin	-	-	-	-	-	-	0.20	0.20
Niacin	-	-	4.67	5.60	6.64	5.98	7.37	6.33

Age group:	16-19 male	16-19 female	Adult male	Adult female	Preg.	Lact.	51+ male	51+ female
Constraint:								
Calories	15.4	11.6	15.0	11.0	12.3	11.3	4.80	16.3
Copper	-	-	-	-	-	-	10.9	1448.3
Vitamin A	-	-	-	-	-	-	-	-
Vitamin C	1.11	1.11	1.26	1.77	-	-	5.10	-
Vitamin D	-	-	-	-	6.50	9.5	-	-
Riboflavin	5.73	4.45	4.24	-	-	5.16	-	-
Folacin	0.20	0.20	-	-	-	-	2.40	47.6
Niacin	7.84	5.87	7.09	0.62	-	-	2.78	-
Zinc	-	-	2.73	12.3	12.3	-	-	-
Iodine	-	-	1.40	-	-	2.25	5.10	-
Vitamin B12	-	-	-	-	-	-	0.41	22.6

The other constraints were less significant because either the number of times that they were binding was low or the cost flexibility of the nutrient was relatively low.

Noteworthy is the fact that iron was not a binding constraint in the various female diets. Also vitamin A, a nutrient that is commonly underconsumed in malnourished areas, and which leads to blindness, when there is deficiency was not binding in any of the diets.

Dairy price increase

A final adjustment to the model presented in Table 2 was to raise the price of cheese and butter to reflect their true market price.[1] Selected optimal diets are in Table 5. Cheese and butter fell out of the optimal solutions.

There was also some change in the binding constraints (Table 6), most notably the inclusion of two amino acid constraints in the two children's diets. The cost flexibility of calories increased, suggesting that butter and cheese were inexpensive sources of calories for AID to provide. Zinc became a significantly binding constraint in the adult diets because it is found mostly in animal products, which no longer figured in the optimal diets. Also, vitamin A became a binding constraint, with implications for xeropthalmia, especially in children.

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[1]The wholesale price for cheese and butter was assumed to be $1.00/lb. This is clearly lower than retail price.

Table 5. Selected optimal daily diets when the prices of butter and cheese are increased to represent the true market price

Age group:	Infants	10-12 male	Adult female	Lact.	Preg.	Adult male
Cost ($)	0.168	0.314	0.306	0.395	0.352	0.389
Food item (g):						
Wheat	115	122	299	162	211	373
Wheat flour	-	81	53	166	-	119
SF bulgar	-	-	84	128	94	98
CSM	42	-	-	-	-	-
ICSM	52	-	-	-	-	-
SF cornmeal	-	134	-	-	-	140
SF sorghum	5	-	-	-	-	-
WSB	107	51	191	253	252	75
Sorghum	-	358	-	81	163	70

Table 6. Cost flexibility of the binding constraints of the optimal diets in Table 4 ($) ($10^{-4}$)

Age group:	Infants	10-12 Male	Adult female	Lact.	Preg.	Adult male
Constraint:						
Calories	32.8	13.0	19.8	24.8	23.0	21.0
Zinc	-	-	5.04	3.43	3.43	4.33
Copper	3.07	-	-	-	-	-
Vitamin A	-	2.86	7.50	6.00	-	3.75
Vitamin C	-	-	-	-	-	0.12
Vitamin D	4.00	-	-	1.00	6.50	-
Riboflavin	-	2.16	-	-	-	9.75
Lysine	-	6.49	-	-	-	-
Threonine	5.95	7.23	-	-	-	-
Valine	0.67	-	-	-	-	-
Iodine	-	-	0.80	1.50	1.50	1.26

Elimination of vitamin supplements

The third question addressed whether or not AID foods could be used in lieu of vitamin supplements during the rehabilitation stage of PEM. The question was tested first from the supposition that if the foods could not meet the total calorie RDA, as well as supplemental RDAs for vitamins and minerals, then the foods could not meet the total calorie and total vitamin and mineral requirements.

The solution to the problem was infeasible, i.e., an optimal diet could not be determined. The model could not provide even supplemental RDAs within the 175 cal/kg limitation. Transforming the equality constraint on calories to a lower bound allowed the model to provide an optimal diet. But, the amount of calories needed to provide this diet was 3.09 times greater than the optimal level.

Direct maternal feeding

The fourth question asked whether or not it was more costly to feed a mother an optimal diet so that she could lactate, or to feed the mother and child separate optimal diets. This question was tested under four sets of assumptions regarding RDA levels, means of transport, amino acid inclusion, and dairy prices (Table 8). In Tables 2, 3, 5, and 7, the optimal diets for a lactating woman, infant, and a normal woman are provided. The cost to feed a lactating woman was less than the cost to feed the mother and infant separately in all four models. Depending on the nutritional constraints and prices used, the cost was from 89 percent to 164 percent greater. In all four cases, the foods in the optimal

Table 7. Optimal diets using foreign shipping exclusively and FAO RDAs

Age group	Infants	7-9	Adult female	Lact.	13-15	16-19	Adult male
Cost ($)	0.105	0.124	0.158	0.210	0.165	0.134	0.186
Food item:							
Wheat	30	-	128	116	-	-	272
ICSM	96	-	-	-	-	-	-
WSB	106	50	75	252	75	75	75
Cheese	86	118	289	73	146	118	195
Butter	-	64	-	103	94	77	96
Sorghum	-	304	-	-	382	282	24
SF bulgar	-	-	120	132	-	-	78
SFCM	-	-	-	-	7	-	-

Table 8. Underlying assumptions for least-cost diet estimations

Table:	2	3	5	7
RDA	FAO	FNB	FAO	FAO
Shipper	Current mix	Current mix	Current mix	Foreign
Amino acids	No	No	Yes	No
Dairy prices	Subsidized	Subsidized	Market	Subsidized

diets for nonlactating and lactating women were the same, except butter was consumed by the lactating woman in the three models with the subsidized butter price and sorghum was consumed with the market butter price. The major difference was that the amount of food consumed increased.

Choice of shipper

The last question addressed whether or not shipping exclusively by foreign flag carriers would have any significant effect on the optimal diets. Table 7 shows the optimal diets when food is shipped by foreign flag and FAO RDAs are used. The cost of the optimal diets decreased from 33 percent for infants to 41 percent for 13-15 year old boys. The only change in the optimal diets occurred in the infant diet and the adult female diet. The change in the infant diet was significant. WSB and wheat consumption increased significantly, while butter consumption fell to zero g and ICSM consumption fell to 96 g.

Conclusions

In this paper, we designed nutritionally adequate diets for the people of Ethiopia while minimizing the cost to AID, so as to increase the effectiveness of famine assistance. In addition, we addressed other related issues and found, by posing five questions, the following:

1. Optimal diets varied in composition and amount by age and sex. Therefore, we recommend that famine relief organizations make provisions to design and provide diets according to age and sex.

2. There were significant differences in the composition and cost of the optimal diets according to the set of RDAs used. The cost of the optimal diets using FAO's RDAs was significantly lower. Therefore, we recommend that the FAO update their RDAs, as the FNB did in 1980. The FAO should also give special consideration to those nutrients that were the most binding in the optimal diets. The FAO should also establish RDAs for the 51+ age group, as the optimal diets for this group were not the same as for other adult men and women. Finally, we recommend that the FAO set RDA levels for the essential amino acids especially for children as our results suggest that lysine, threonine and valine may be binding constraints in childrens' diets.

3. Folacin, niacin, and vitamin D were limiting in at least half of the diets, and the cost flexibility of these nutrients was relatively high. Therefore, we recommend to manufacturers of high-nutrient mixes that they concentrate their efforts on producing and including higher levels of these nutrients.

4. The cost of feeding a mother so that she may lactate was significantly lower than the cost of feeding the mother and infant separate optimal diets. Therefore, we recommend that breast feeding continue to be encouraged by the FAO and development agencies. The cost effectiveness and the health implications of breast feeding make it a superior option to formula feeding.

5. As the cost flexibility measures indicate, calories were the most costly nutrient to provide. Therefore, we recommend that famine assistance should concentrate on providing a sufficient amount of

calories to the malnourished. This finding agrees with development literature which has concluded that the dominant malnutrition problem in large populations is insufficient intake of calories and not protein (Berg, 1981, p. 5).

6. An optimal diet for PEM rehabilitation of young children cannot be designed eating food only. Therefore, we recommend that relief agencies continue to use vitamin and mineral supplements in the treatment of PEM.

7. The type of transportation used to ship the famine aid did not significantly alter the optimal diets. However, the cost to ship by foreign carrier was much less than by domestic carrier. Therefore, we recommend that AID first offer domestic carriers the option to ship the food aid at the same price foreign carriers charge. If this is not feasible, we recommend that AID ship food aid by foreign carrier.

In summary, we hope that the results in this paper can provide both dietary guidelines for the malnourished in famine-stricken areas, and guidelines for improving U.S. agricultural policies and their implemementation. In the future, if RDAs for each stage of malnutrition can be developed, a dynamic programming algorithm could be used to evaluate and improve rehabilitative therapy.

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GENERAL CONCLUSIONS

This thesis has demonstrated the broad applicability of a linear programming approach to problems of malnutrition ranging from starvation in Ethiopia to obesity in America. It has also demonstrated how a linear program can be used within an institutional setting.

The first essay, "Least-Cost American Diets for the 1980s: The Impacts of Improved Information on Nutrition and Health," examined the impact of increased nutritional information on least-cost diets. The essay also addressed the impact of health recommendations upon optimal diets. The results suggested that:

1. Increased nutritional information in the form of a larger set of RDAs increased the variety and the cost of optimal diets.

2. Health recommendations further increased the variety and the cost of the optimal diets.

In the second essay, "A Comparison of Type A and Strictly Least-Cost Diets with Plate Waste Considerations and Added Nutrients," optimal diets for grade school and high school children were generated. The results suggested that:

1. Optimal diets for grade school children are different than optimal diets for junior high and high school children.

2. Optimal diets with consideration for palatability are inexpensive when compared to the current cost of a lunch in the National School Lunch Program.

In the third essay, "Least-Cost Diets in U.S. Famine Assistance to Ethiopia," optimal diets were designed for each population target group in Ethiopia. The results suggested that:

1. Breast feeding is the most cost efficient means of feeding infants.

2. Optimal diets vary according to age, gender, and dietary recommendations used, especially between adults and children.

3. A least-cost diet cannot be designed during the rehabilitative stage of PEM without vitamin and mineral supplements.

Reviewing the three essays together one can see that:

1. Optimal diets vary according to age and sex.

2. Variety of the optimal diets increases with dietary complexity.

3. Dairy items were significant activities in all optimal diets, while meat items became activities in the optimal diets only with the inclusion of palatability constraints.

4. Shadow prices alone may not be the best way to view the cost of adding additional inputs to a consumption process, especially when the other inputs are measured in different units.

Like any model in economics, the results of these analyses are not intended to be followed to the letter, nor are they of use only to economists. The results do give general directions for future research:

1. The refinement of current RDAs especially those which have been both binding in three essays and which consumptions studies show are traditionally underconsumed.

2. The inclusion of RDAs for nutrients which currently do not have a specific RDA.

3. The setting of upper limits on the consumption of food additives along with the delineation of the additive composition of food.

The type of analyses presented in these three essays could be easily used by individuals with microcomputers to design least-cost diets within their own institutional setting, because the marginal cost of designing these diets is very low. For example, hospitals could use it to specifically meet certain therapeutic RDAs while still allowing for palatability by allowing the patient to list acceptable foods.

Finally, this thesis is a demonstration of the interdisciplinary work that Carol Tucker Foreman (1978) called for in her address to the AAEA in 1978, i.e., for agricultural economists to focus more attention on the problems of food and nutrition. It is hoped that further research will be done in this area and that agricultural economics and nutritional journals will not shy away from publishing such research.

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